Developing the STELLA Model for a DSS for Mitigation Strategies for Transportation Infrastructure: Introduction to STELLA

By Silvana V Croope

* A working paper submitted to the University of Delaware University Transportation Center (UD-UTC)

January 29, 2010
**DISCLAIMER:**

The contents of this working paper reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.
# Table of Contents

Table of Contents ........................................................................................................................................ 3  
List of Figures ............................................................................................................................................. 4  
List of Tables ............................................................................................................................................... 5  
Introduction ............................................................................................................................................... 6  
  Background ........................................................................................................................................... 6  
  Objective of this Working Paper ............................................................................................................. 9  
  Approach to Model Development in STELLA ........................................................................................ 9  
Basic Knowledge for Working with STELLA ............................................................................................. 11  
  System Dynamics Language .................................................................................................................. 12  
  Rules ...................................................................................................................................................... 15  
  Templates ............................................................................................................................................... 15  
  Constructing More Complex Sentences ................................................................................................. 17  
  The Process: Writing in STELLA ........................................................................................................... 19  
  Benefits of Using STELLA ................................................................................................................... 25  
An Initial Approach for Building a Model in STELLA for CIR-DSS ...................................................... 26  
Summary and Related Work ..................................................................................................................... 32  
Acknowledgements ................................................................................................................................... 32  
References .................................................................................................................................................. 33
List of Figures

Figure 1 CIR-DSS System Dynamics Diagram ................................................................. 6
Figure 2 CIR-DSS Model-2 in STELLA ......................................................................... 10
Figure 3 Main Chain and Attribute Tracking Infrastructure Types – STELLA ............. 10
Figure 4 Stocks Types in STELLA ................................................................................ 12
Figure 5 Flow Types in STELLA .................................................................................. 13
Figure 6 Converter Uses .............................................................................................. 15
Figure 7 Possible Ways to Link Sentences .................................................................. 16
Figure 8 Templates Diagram Examples in STELLA ...................................................... 17
Figure 9 Reinforcing and Counteracting Loop Example ............................................... 18
Figure 10 Writing Steps in STELLA ............................................................................. 25
Figure 11 Critical Infrastructure Resilience DSS Improvement Diagram ...................... 27
Figure 12 Reference Behavior Pattern for System "As Is" ........................................... 29
Figure 13 Reference Behavior Pattern for System "To Be" ............................................ 31
List of Tables

Table 1 GIS Analysis Results for Seaford Transportation Infrastructure ......................... 7
Table 2 HAZUS-MH MR3 Analysis Results for Seaford Transportation Infrastructure ...... 8
Table 3. Stocks - Functions and Examples ........................................................................ 12
Table 4 Flow Types in STELLA ......................................................................................... 13
Table 5 Infrastructure Template: Overshoot and Collapse .............................................. 20
Table 6. Infrastructure Template: Slippery/ Sticky Perceptions ........................................ 21
Table 7. Infrastructure Template: Main Chain................................................................. 22
Table 8 Infrastructure Template: Attribute Tracking......................................................... 23
Table 9 Infrastructure Template: Relative Attractiveness ................................................ 24
Table 10 CIR-DSS Elements in STELLA Model-Construction and Learning Processes ...... 28
Introduction

Background
This working paper serves as background research for the PhD dissertation titled “Managing Critical Civil Infrastructure Systems for Disaster Resilience: A Challenge.” The overall objective of this research is to develop a Decision Support System to improve the resilience of critical infrastructure. This involves the exploration of the potential impacts of natural disasters on infrastructure operation and management. This includes understanding the nature of operations and management, the data and tools to support decision making and an analysis of the consequences of failure or degraded operations and performance. This also includes the use of existing computational systems to develop a geographical context, civil infrastructure systems analysis, asset management systems, and insights into mitigation strategies to the development of the system.

The model, referred to as the Critical Infrastructure Resilience Decision Support System (CIR-DSS), used the concept of resilience to support infrastructure decision making using Systems Dynamics. The framework is shown in Figure 1.
To implement this framework, inputs to the system dynamics model are generated using GIS (ESRI 2007) and HAZUS-MH MR-3 (FEMA 2007b) that describes the overall analysis of the resilience of an infrastructure system. The system is then analyzed using systems dynamics. STELLA (isee systems 2008) is graphically oriented modeling software used to develop the systems dynamics models. The June 25, 2006 flood event in Seaford, Delaware is used to illustrate the concepts and demonstrate how the complex system changes over time.

The analysis developed in GIS and HAZUS-MH (Croope 2009) is not repeated in STELLA. GIS and HAZUS-MH are used to generate maps for vulnerability assessment, and estimate exposure. The Level 2 analysis in HAZUS-MH organizes and structures relevant data. The results from GIS are shown in Table 1. The maps originally developed are not readable in this table, but included to demonstrate how to organize results.

**Table 1 GIS Analysis Results for Seaford Transportation Infrastructure**

<table>
<thead>
<tr>
<th>System</th>
<th>Results</th>
<th>Description</th>
</tr>
</thead>
</table>
| GIS (ArcInfo)   | ![Map Images](image1.png) ![Map Images](image2.png) ![Map Images](image3.png) ![Map Images](image4.png) ![Map Images](image5.png) | From the left to the right:  
- Detours Set Up during the Flood of June 25, 2006 (DelDOT’s paper map),  
- Seaford Study Area,  
- Seaford Area Elevation Profile in 3D Image,  
- Rainfall recorded in Seaford area,  
- Flooded Area and Bridges impacted in Seaford area,  
- Seaford Road Network and Detours Analysis,  
- Location of Damaged Infrastructure in the Seaford Flooded Area.  
Event information supplied and maps developed can help direct relief supplies to areas of critical need and give out-of-state teams knowledge of local terrain and access to places. |

The results from HAZUS-MH are shown in Table 2, including maps, tables and reports, helping organize all existing outputs.
Table 2 HAZUS-MH MR3 Analysis Results for Seaford Transportation Infrastructure

<table>
<thead>
<tr>
<th>System</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
</table>
|                                  | From the left to the right:                                             | • Base Map built in HAZUS-MH for Seaford Area (include limited area around US13),  
  • Seaford Area Annual Losses Map of Depth,  
  • “What if” Levee Protection Scenario,  
  • “What if” Flow Regulation Scenario,  
  • Floodwater Velocity Estimation Scenario,  
  • Damage related to US13 in Sussex County,  
  • (There is an embedded mitigation measure for “warning” not reflected in the images).  |
| HAZUS-MH MR3                    | Organized information for helping interpret results (left to right)     | • Hazards Identification for Working with HAZUS-MH,  
  • Hazard Identification and Characterization,  
  • Profile Hazard for Case Study,  
  • Similar Federal Disasters and Damage between 1962 and 2006 in Sussex County,  
  • Federal Disasters Damage Graph - Sussex-DE,                                                                                                      |
|                                 | Analyses Results                                                        | • Summarized Report for Transportation System Dollar Exposure,  
  • Summarized Report of Estimation for Debris (require 112 truckloads),  
  • Summarized Mitigation Measures based on HAZUS-MH and History for Transportation Infrastructure – Roads,  
  HAZUS-MH gives no value for direct economic loss analysis for transportation.  
  Transportation Inventory table is adjusted in excel for modeling.                                                                                     |
Once GIS and HAZUS-MH have been used to generate some results important to the overall analysis of the resilience of an infrastructure system, the resilience of the system is better analyzed using systems dynamics. This is what STELLA is being used for. In other words, System Dynamics modeling the transportation infrastructure problem helps describe the state of the system following the June 25, 2006 flood event, and how the complex system changes over time. Once this part of the problem is solved, the results are organized for presentation to the target audience. Systems Thinking skills include trade-offs of time, and management possibilities, and forecasting factors that are included in the model.

The items in *italics* in the Analysis Results for HAZUS-MH are important for the model in STELLA. These items in italics include data used in STELLA and mitigation options according to the FEMA STAPLEE criteria (Rock Island County 2008) for being a feasible mitigation measure. The mitigation options include enhancing the resilience of the system as opposed to a regular rebuilding or repair of the infrastructure system segments according to its original design. The Highway inventory in HAZUS-MH is not in a proper format to be an input in STELLA. This data exported to EXCEL is used in the modeling and simulation process imported into STELLA, which each named column in EXCEL must match the elements in the model in STELLA. Also, to simplify the demonstration of the model, a sample from this infrastructure was determined – US13.

The data related to US13 was obtained by comparing the Highway inventory from HAZUS-MH, and the road data from DataMIL clipping it to fit the study region in HAZUS-MH and then highlighting the HAZUS-MH segment links to identify their given identification code. This process used the Select Feature tool, because when opening the inventory table out from ArcMap or HAZUS-MH interface, the available tables did not carry together in the information for “name” of US13 segments and the value for “cost”. Also, to highlight US13 in GIS for a qualitative network assessment, the creation of this new layer helps set up the boundary for the analysis later on. The model in STELLA cannot handle these geographical spatial analyses, therefore the need for integrating the results from these different systems.

**Objective of this Working Paper**

This working paper provides background on STELLA. The objective is to

- define the terminology and concepts that are used in subsequent working papers and the thesis.
- describe how the model was developed in the STELLA software to simulate different scenarios to support Decision Making for improving system resilience.

**Approach to Model Development in STELLA**

Initially the model development in STELLA used the Main Chain infrastructure type. As the model development proceeded, it became clear that this structure was not going to
address the objectives of this research, and included tasks that can be performed by existing software to generate the information needed to analyze system resilience.

The second approach recognized that system resilience is an attribute of the system being investigated. This new approach used the Attribute Tracking infrastructure in STELLA. The main idea for tracking the attribute resilience is shown in Figure 2.

![Figure 2 CIR-DSS Model-2 in STELLA](image)

The Attribute Tracking system infrastructure has a different shape than the Main Chain infrastructure. There are fewer elements being added or subtracted in the analysis process in the Attribute Tracking infrastructure. The system tracks the changes of the system elements’ quality and behavior through time. Figure 3 shows examples of both the Main Chain and the Attribute Tracking infrastructure types developed in STELLA.

![Figure 3 Main Chain and Attribute Tracking Infrastructure Types – STELLA](image)

The model developed is not complete or perfect, because as one can see, there are several different units in this framework sequence, and STELLA does not work this way. However, this is the basis for model development in STELLA that reflects the elements of Figure 1.

Working with STELLA implies working with both: model construction and learning process. During the model construction it is important to follow this sequence (isee systems 2004):

- define the issue – dynamic thinking;
- develop the hypothesis – 10,000 meter and system as a cause thinking;
- test the hypothesis – to replicate the dynamic phenomenon, and for robustness (model in steady state, test one thing at the time, to find limitations and when it stops making sense). Robustness tests help building confidence in model’s formulations and identify high leverage points (big reaction);
- draw conclusions; and
- assess robustness.

These analyses developed in STELLA work with some elements of the framework (mostly not included in initial GIS and HAZUS-MH analyses), including

- Critical Infrastructure Management System including its subsystems
  - Functional (Asset Management) Subsystem (e.g. reconstruction cost),
  - Financial Subsystem (e.g. financial resource source – FEMA),
  - Decision Making Subsystem (e.g. DelDOT decision-maker and protective measures decisions);
- Resilience Management Information System (e.g. disaster timing and resilience of calculations), and
- Results Presentation System (e.g. user and agency benefits).

Because STELLA covers these different components of the framework, the title given to this model and simulation part is “Resilience of Infrastructure Management and Information System”. The interface of the model built in STELLA carries this title. Before presenting the model development in steps and the final interface, the required knowledge, skills, and data are described.

**Basic Knowledge for Working with STELLA**

The STELLA software is a product from i-see™ systems Inc. This section presents some of the basic elements and their representations according to the guide for STELLA software (isee systems 2004). The subsequent working paper presents an initial approach for using STELLA for the CIR-DSS framework.
STELLA uses a graphical user interface to capture dynamic behavior of the system in a causal loop diagram, also known as a stock and flow diagram. The graphical representation uses a language - a series of symbols and constructs to capture the dynamic behavior of the system.

**System Dynamics Language**

The STELLA software guide starts with the explanation of stocks (nouns, e.g., population, water, quality, commitment), which can be *reservoirs, conveyors, queues* and *ovens*, shown in Figure 4. They exist at a point in time, and are designated by capitalizing the first letter. Stocks tell you how things *are* in a system.

![Figure 4 Stocks Types in STELLA](image)

*Source: Modified from isee systems (2004).*

Each stock has a different function (characterized by a noun), which is shown in summary in Table 3.

<table>
<thead>
<tr>
<th>Stocks</th>
<th>Function(s)</th>
<th>Example(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>Total number of entities - houses the net of what has flowed in, minus what has flowed out.</td>
<td>Water, population, cash.</td>
</tr>
<tr>
<td>Conveyor</td>
<td>The quantity that arrives at the slat - the one arriving at the “first slat” gets on and occupies it alone (not sharing the space), and rides (transit time) until the conveyor deposits it at the other end.</td>
<td>Like escalators - pipeline delays, aging chains.</td>
</tr>
<tr>
<td>Queue</td>
<td>For discrete event simulations. A line that is developed when things arrive at a rate that exceeds the capacity to process them. Retains both arrival integrity and batch size.</td>
<td>Cars stacking up at the tollbooths or cars amassing at a rotary (roundabout).</td>
</tr>
<tr>
<td>Oven</td>
<td>For discrete event simulations. Entity arrives, if the oven is currently baking (busy, or in operation), the entity waits (in a queue or a reservoir) and when (process) completely done, it exits. The entity that’s waiting enters up to the capacity of the oven (limits/thresholds determined), or until the doors open time expires. Entity then bakes/operates for the length of the oven’s bake time, and it’s then discharged.</td>
<td>Like elevators, depends on door open or closed to ride, and can have a queue waiting to ride it.</td>
</tr>
</tbody>
</table>

*Source: Adjusted from isee systems (2004).*
Another basic element is flow. Flows are designated using verbs. Verbs exist over time, are not written with capital letters, and indicate how things are going. Flows occurring update the magnitudes of stocks. Without any flows, system conditions remain static. Flows are responsible for the dynamics of the system, and can be physical (e.g., eroding, delivering, dying, in-migrating, and raining) or non-physical (e.g., building self-confidence, discussing, and learning) in nature.

There are two flow varieties, and one wrinkle shown in Figure 5. The flow characteristics per type are presented on Table 4.

![Figure 5 Flow Types in STELLA](source: isee systems (2004)).

**Table 4 Flow Types in STELLA**

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniflow</td>
<td>- standard type, unidirectional indicated by the arrowhead;</td>
</tr>
<tr>
<td></td>
<td>- uniflow pointing <em>into</em> a stock - <em>fills</em> the stock (and vice versa);</td>
</tr>
<tr>
<td></td>
<td>- if inflow calculated value is negative (flow drains the stock), value is over-ridden by a value of zero - inflows cannot operate as outflows.</td>
</tr>
<tr>
<td>Biflow</td>
<td>- bi-directional flow, flow volume goes in <em>both</em> directions, either into or out of a stock;</td>
</tr>
<tr>
<td></td>
<td>- general use rule: processes governing inflow/outflow to a stock are identical in nature;</td>
</tr>
<tr>
<td></td>
<td>- example: velocity.</td>
</tr>
<tr>
<td>Unit Converted Flow</td>
<td>- used to make sense to convert the units-of measure of what’s flowing, while it’s flowing;</td>
</tr>
<tr>
<td></td>
<td>- example: pull two Hydrogen and one Oxygen atom out of respective stockpiles and make one water molecule, rather than <em>three</em> individual molecules.</td>
</tr>
</tbody>
</table>


By putting together nouns and verbs in sentences STELLA captures the behavior of the system. There are two types of sentences – simple or compound. Simple sentences involve one stock, with associated flow(s). Compound sentences (or infrastructures, spinal cords, or main chains), involve two or more stocks linked by at least one flow. The sentences must respect unit consistency, and conservation laws (law of conservation of matter and energy), unless dealing with non-physical variables (with the exception of the quantity of time). The addition or subtraction of quantities of non-physical variables
does not interfere with the condition of others (e.g. knowledge, anger, commitment) as they do not operate in a zero-sum manner.

The real challenge appears when sentences are linked. The process initially follows operational thinking. As issues being modeled get more complex, two other types of thinking skills are needed for building models: closed-loop and non-linear. There are two possible ways to use operational thinking to link sentences: stock to flow, or flow to flow. To link stock to flow or flow to flow, a wire called connector is used. There are two types of connectors:

1. A solid wire – the action connector, which transmits an action, not information, or ends a process;
2. A dashed wire – the information connector, which serves as an input, begins a process, or is used to arrive at a decision.

There’s also a decision logic element, a space-compressed Decision-Process Diamond (DPD) that is not usually visible in the model representations. The DPD is usually shown as a diamond-shaped geometric figure. The idea is that information leads to a decision, and a decision leads to an action. It is where processes in a sub-model level/hierarchy can be held. This feature can be used to improve the model’s visualization.

The action wires in a model convert the resulting decision into an action that is manifested as a change in the volume of flow. Only information connectors stick into DPD’s, but both types of wire can come out of a DPD so that action will be taken as a result of the decision and information about the decision or the inputs to that decision. No connectors can be used to represent a conserved-flow linkage. Stocks do not flow through the wires. Flows transport and wires transmit. Connectors are inputs and outputs, not inflows and outflows. This is confirmed when tracking information to look at the different status of resilience of the infrastructure system in the model developed.

Another element in the STELLA language is the converter, which is used to represent productivity. The converter plays the role of an “adverb”, modifying the verb (or flows). The converter tells about the how much per unit of the driver is contributing to an activity being made, a flow, or a stock of that activity. It is expressed in the relevant units (e.g., knowledge/time). An example of the algebra is shown in Equation 1.

**Equation 1 Converter Example for Working with STELLA**

\[
\text{your learning} = \text{your reading} \times \text{your learning productivity}
\]

\[
\left(\frac{\text{knowledge}}{\text{time}}\right) \times \left(\frac{\text{pages}}{\text{time}}\right) = \left(\frac{\text{knowledge}}{\text{page}}\right)
\]


Other possible uses for converters are: doing algebraic operations (summing or division), representing exogenous inputs, and substituting either stocks or flows that are
still being chosen to be represented in the model. Converters can also change over time. Figure 6 shows examples of converter uses.

![Figure 6 Converter Uses](image)

**Figure 6 Converter Uses**
Source: Modified from isee systems (2004).

**Rules**

To put together the elements to write sentences, two rules must be observed. The first is to respect unit consistency (units-of-measures) between stocks and the attached flow(s) - they must be the same, except when using unit conversion. The second is to respect conservation laws (same as matter and energy in physics). However, this law can be legally violated to fit models by making a *conscious decision* to end a particular chain by not modeling nonessential elements, and when using a stock to represent a *non-physical quantity*, other than the quantity of time. Non-physical variables do not obey this law, and do not operate in a zero-sum manner (e.g., anger, knowledge). The addition or subtraction of non-physical quantities does not interfere with the condition of others.

**Templates**

*STELLA* models using the stocks, flows, connectors, and other elements such as DPD's, are organized in templates that can represent flow formulations such as the *stock-generated* formulation (called External Resource Template), or the *flow-generated* formulation (called Co-flow Template), as shown in Figure 7. The clouds refer to a starting or ending point related to the subject being addressed.

Some of *STELLA*'s common templates that can be used to guide building models are briefly listed and characterized below.

- **External Resource Template** – used when some resource, other than the stock to which the flow is attached, provides the basis for producing the flow. Rather than the stock generating its own inflow or outflow, the flow is generated by a second stock (an external resource), which has an associated productivity.

- **Co-flow Template** (coincident flow) – useful to represent an activity that is driven by another activity, or to track an attribute associated with a stock. The co-flow typically is defined as the product of two flows.
• Draining Template – used to represent a passive decay process, where the flow is generated by the stock out of which it is flowing. The flow (an outflow from the stock) is the product of the stock and a loss fraction, or the stock divided by a time constant (the reciprocal of the decay fraction). Indicates the average length of time resides in the stock, in steady-state.

• Stock-adjustment Template – used to represent situations in which a stock adjusts to a target value, and the way in which perceptions, opinions, and the like, are adjusted. The flow is a bi-directional! Whenever a discrepancy exists between the stock and the target, the flow will adjust the stock toward the target. Both the target and the adjustment fraction/time constant are usually converters but can be stocks.

• Compounding Template – used to represent a self-reinforcing growth process - flow generated by the stock into which it is flowing. The inputs to the flow are the product of inputs. Compounding fraction (a stock or a converter) has its units-of-measure as units/unit/time. The units are denominated in the stock. Compounding fraction is equal to how many new units are produced by each existing unit within the stock, per unit of time.

Examples of template diagrams are shown in Figure 8.
Constructing More Complex Sentences

To construct more complex sentences in STELLA such as closed loop and non-linear thinking, feedback loop parameters are allowed to vary, and feedback loops are extended to involve more than one sentence. This enables feedback loops to a richer variety of dynamic behavior. This is represented as a graphical function in the STELLA software, which can be added to the diagram and represented by a sign of loss of innocence (~) – a relationship between an input variable and an output variable. The graphical function:

- indicates how an output variable will change as the associated input variable changes (a consequence of movements in some other variable – e.g. the impact of saturation);
- expresses the bi-variate relationship by making use of a sketchpad with a grid on it, rather than resorting to mathematics;
- draws the relationship envisioned (by capturing a hypothesized relationship between two variables whose interaction assumes all other things held constant);
- enables non-mathematically-inclined people to express relationships largely limited to the domain of mathematicians;
- represents structural relationships within the model, meaning they are not graphs of model output over time;
enables feedback loops to change in strength (shifts in feedback loop dominance) over the course of a simulation.

The slope of the graphical function should not change direction. If it does, there may be some implicit inclusions of the impact of one or more variables in the formulation of the relationship. The graphical function must also have some elasticity of variables over the range (outside its historical operating range), to allow the model to result in genuine new insight, which is possible within the STELLA software guidelines.

Shifts in feedback loop dominance can cause systems to generate surprises, and be responsible for the nonlinear responses - large pushes can yield barely discernible reactions, and small changes can unleash avalanches. These shifts are caused by variation (e.g., implemented by using a graphical function) in the associated parameter values associated with the loops.

Feedback loops can perform in different ways. For example, they can be a reinforcing loop, or a counteracting loop. They both serve to better balance the model and reflect an event; however, a counteracting loop is considered better for increasing control of the dynamic behavior than reinforcing loops. An example for these types of feedback loops are shown in Figure 9.

![Reinforcing and Counteracting Loop Example](image)

**Figure 9 Reinforcing and Counteracting Loop Example**
Source: Modified from isee systems (2004).

In summary, the benefits for using feedback loops are that they:

- enable systems to maintain internal balances, and also to grow;
- guide evolutionary adaptation, and preside over catastrophic collapses;
- self-generate all manner of dynamic behavior, and set in motion an ongoing dynamic (a more than one-time response);
- relates the strengths of the various feedback loops that make up the system to the dynamic pattern traced, and how those strengths wax and wane over time. The graphical function serving as a coupling point between loops is often the vehicle for enabling such waxing and waning to unfold.
More complex formulations are possible in STELLA software through five different infrastructures templates. The five generic infrastructures can serve as nuclei for constructing models, which combine paragraphs and give rise to their own dynamic behavior. The templates for the infrastructures and their respective details are shown in Table 5 (overshoot and collapse), Table 6 (slippery/sticky perceptions), Table 7 (main chain), Table 8 (attribute tracking), and Table 9 (relative attractiveness).

The Process: Writing in STELLA

The writing process in STELLA uses the principle of “keep it simple.” This principle recognizes that the model is not reality; it is just a representation to try to account for the phenomena (isee systems 2004). The steps involved in writing the system model in STELLA are shown in Figure 10 Writing Steps in STELLA.

Constructing a model and integrating learning processes into the model should be done in parallel to help make sense of the formulation and ensure a proper representation of the issues. The sequence of steps in both the model construction and learning processes is far from linear. The feedback arrows represent learning, and the large two-headed arrows link the parallel streams visually reinforce the interplay between them, each informing the other. Therefore, as soon as an issue is identified, the learning process must be developed in parallel with the model development to better integrate the overall context into the analysis. To be understood, both processes must be guided by a sharply-focused issue, couched as a dynamic phenomenon.

In other words, there are basically two purposes for STELLA-based modeling efforts – the creation of a research tool, and the creation of a learning tool. A single model can serve both functions, but in practice this rarely occurs. The basic differences between these tools are:

- research tools tend to be answer generators, often with large models, placing value on highly-precise parameter, and generating numerically accurate results;
- learning tools inspire insights, catalyze changes in the assumptions underlying the mental model, relatively small, with (only) relative (internally-consistent) parameter values (rather than absolute and numerically precise ones).
### Table 5 Infrastructure Template: Overshoot and Collapse

<table>
<thead>
<tr>
<th>When to Use</th>
<th>For physical, biological, and social systems. Transition from growth to steady-state is not smooth. They grow rapidly, peak, and then collapse to a lower steady-state value (e.g., extinction).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Description (example)</td>
<td>Population consumes a non-renewable resource. Resource scarcity collapse population. No possible recovery.</td>
</tr>
<tr>
<td>Dynamic Behavior</td>
<td>Growth phase of the pattern looks like S-shaped. First growth expands rapidly - resource is abundant, compounding process dominates behavior. Resources drawn down, death rate loop gains strength, growth slows (Population close to maximum value). Population cannot be sustained - Resource continues to decline. Outflow from Population becomes greater than the inflow, and remains. Time is not doubled or tripled before system collapses - compounding processes generate exponential, not linear, growth.</td>
</tr>
<tr>
<td>Variations on Generic Theme</td>
<td>Variation of the generic overshoot and collapse structure – allows resource regeneration which rate declines as the level of the resource declines. This structure can generate a rebound from the collapse under certain situations, but resources per pop must go to zero before Resource reaches zero. Resource = zero, no basis for system regenerating.</td>
</tr>
</tbody>
</table>

Table 6. Infrastructure Template: Slippery/ Sticky Perceptions

<table>
<thead>
<tr>
<th>When to Use</th>
<th>Existence of a rate asymmetry, perceptions is adjusted. This structure captures it without needing a lot of technical wizardry (e.g., consumers get aware of a product quality problem).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Description (example)</td>
<td>A stock-adjustment template with one wrinkle. Adjustment time is a variable, not a constant - depends on the Perceived State and the actual state relationship. Actual State &lt; Perceived State = small adjustment time (perception process slippery downward). Actual State &gt; Perceived = large adjustment time (sticky upward adjustment).</td>
</tr>
<tr>
<td>Dynamic Behavior</td>
<td>Depicts the response - an initial steady-state, to actual state - 40% step-increase and step-decrease. Responses are not symmetrical. Completed downward adjustment takes few time periods (slippery), while upward adjustment takes nearly 50 time periods (sticky).</td>
</tr>
<tr>
<td>Variations on Generic Theme</td>
<td>Allow the adjustment time to be represented by a graphical function, rather than by using an algebra. This enables speed of adjustment to vary more continuously (not only one value if actual is less than perceived, and another value otherwise).</td>
</tr>
</tbody>
</table>

Table 7. Infrastructure Template: Main Chain

<table>
<thead>
<tr>
<th>When to Use</th>
<th>Also called spinal cord – useful to represent a sequence of stages through which stuff passes. Example, aging sequential phases of a plant or animal.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Description (example)</td>
<td>The chain of reservoirs is fed at the front-end by being born single flow. Two outflows drain each reservoir - a flow-through that moves stuff on to the next “phase” (age category), and an exit flow that drains stuff out of the chain. Associated with each exit flow is death rate. All outflows in the chain are represented by the Draining template.</td>
</tr>
<tr>
<td>Dynamic Behavior</td>
<td>In steady-state they distribute total contents among the chain stocks in proportion to the each associated stock average residence time, which is determined as some blend of its flow-through and exit time constants.</td>
</tr>
<tr>
<td>Variations on Generic Theme</td>
<td>Classic form - Main Chain is fed with an inflow only into the first stock in the chain. Inflows added to any other stock modifies the classic structure. Replacing reservoirs with conveyors is another option; and varying parameters associated with the draining processes (e.g., draining fractions) rather than remaining constant, is also another option.</td>
</tr>
</tbody>
</table>

Table 8 Infrastructure Template: Attribute Tracking

<table>
<thead>
<tr>
<th>When to Use</th>
<th>Used to “track” an attribute associated with a stock. Structure creates an attribute moving exponential average, which gives less weight, progressively, to the further back in time numbers being used in the calculation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Description (example)</td>
<td>Attribute being tracked: skill level of a population of employees. Moving average skill level calculation for the overall population (per employee): total number of employees divided into the total amount of skills they possess. Each employee hired carries an average amount of skill (a co-flow process). Each one who leaves (also a co-flow process) carries an average level of skill. The latter amount is related to the current average skill level of the population. The relationship is the multiplication of the average by a leaver bias. Bias greater &gt; 1.0, leavers takes something greater than the current average; if = 1.0, leavers take the average; if &lt; 1.0, leavers take less than the average when departing. Other Total Skills stock inflow that is developing skills occurs independently of flows of employees. Developing skills flow formulation is the External Resource process (not always the case).</td>
</tr>
<tr>
<td>Dynamic Behavior</td>
<td>Infrastructure initialized in steady-state (hiring = leaving), the leaver bias is zero (those leaving are not taking existing employees’ average level of skills, despite new employees getting in having lower skill). To system remain in steady-state; it must offset the difference of the employee’s population skills through the developing skills inflow. The result = existing population slow decay of the average skill level - down to a new, lower steady-state value.</td>
</tr>
<tr>
<td>Variations on Generic Theme</td>
<td>Variations on this structure are achieved by varying the parameters associated with the structure. Variations can be driven by the average level of the attribute. Example: leave rate, leaver bias, learning productivity, and the average skill of new employees, could all be represented as graphical functions of average skill level.</td>
</tr>
</tbody>
</table>

Table 9 Infrastructure Template: Relative Attractiveness

<table>
<thead>
<tr>
<th>When to Use</th>
<th>Useful to generate an index of attractiveness that is comprised of a set of attractiveness components - a weighted average of the components.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Description (example)</td>
<td>Example: a population center with three attractiveness “factors” attached to sliders, which are chained - 100% of the weight can be distributed.</td>
</tr>
<tr>
<td>Dynamic Behavior</td>
<td>Initialized infrastructure is to generate a relative attractiveness steady-state. Attractiveness components (density of development, unemployment, and housing availability) = to values for each component taken on by the town/city/region to which this population center is being compared. Figure shows, attractiveness increase from employment (2) is somewhat offset by a decrease in attractiveness from the higher development density (3), caused by the increase in business structures numbers. Playing with the weightings and re-simulating the test shows the impact changes.</td>
</tr>
<tr>
<td>Variations on Generic Theme</td>
<td>By adding more attractiveness factors and allowing the factors weightings to vary (rather than remain fixed). One apparent human perception process characteristics is that a particular component of attractiveness being satisfied, people tend to weight it less. Based on this notion, weights can be set up to vary (e.g., Maslow’s hierarchy of needs).</td>
</tr>
</tbody>
</table>

This means, it is important to follow this sequence when constructing a model, according to Figure 10:

- define the issue – dynamic thinking;
- develop the hypothesis – 10,000 meter and “system as a cause” thinking;
- test the hypothesis – to replicate the dynamic phenomenon, and for robustness (model in steady state, test one thing at the time, to find limitations and when it stops making sense). Robustness tests help building confidence in model’s formulations and identify high leverage points (big reaction);
- draw conclusions; and
- assess robustness.

In the learning process, as shown in Figure 10, the strategy can be passive or active, although STELLA privileges the active strategy including exercising, extending, and thus constructing, using empathy thinking skills.

In fact, capturing system feedback in a loop structure in an operational way is the strength of the system dynamics model and is the main difference between building models with tools like spreadsheets versus using the STELLA software.

**Benefits of Using STELLA**

Some benefits for using STELLA are:
• the language increases the accuracy and clarity of verbal descriptions, ambiguities diminish, and communication becomes much more efficient and effective;
• the software provides a check on intuition, and also provides a vehicle for building an understanding of why;
• the tools facilitates putting together in an organized and clear way the qualitative and quantitative approaches present in the CIR-DSS framework; and
• the tool enables an easier operation, demonstration, and replication of the CIR-DSS framework, serving as the basis for analyzing different types of infrastructure.

The use of STELLA for the CIR-DSS framework requires the use of several different infrastructure templates to build the full model. The identified templates at present are the Main Chain for the overall CIR-DSS framework, the Attribute Tracking for the overall resilience improvement goal of the infrastructure system, and the Relative Attractiveness for identifying better projects choices to improve infrastructure systems (e.g., maintenance or reconstruction, or new projects according to mitigation strategies).

In the next section an initial approach for using STELLA for CIR-DSS is described.

**An Initial Approach for Building a Model in STELLA for CIR-DSS**

Building on Figure 8 (templates diagrams), Table 5, Table 6, Table 7, Table 8, and Table 9 (infrastructure templates), and the CIR-DSS framework shown earlier (Figure 1), this section describes the initial approach to building a model for CIR-DSS in STELLA. Before developing the details, it is important to understand that improving the resilience of the critical infrastructure system is a process of continuous improvement. Figure 11 represents a mechanism for learning and evolving assuming the occurrence of a disaster as a starting point. The increasing knowledge through time enables better management of critical infrastructure systems as the decision making process evolves, considering past events, variables, and stakeholders involved in this type of scenario.
Table 10 presents a summary description of each of the items for building the model in STELLA and the overall learning process related. Recognizing that the CIR-DSS has several subsystems, and a step-by-step way for capturing the dynamics involved in the issue of resilience of critical infrastructure systems in a post-disaster context, the model is also broken into parts to fit each interaction among these subsystems.
### Table 10 CIR-DSS Elements in STELLA Model-Construction and Learning Processes

<table>
<thead>
<tr>
<th>Define the Issue</th>
<th>Model-construction Process</th>
<th>Learning Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>The model is intended to help supporting decisions to improve resilience of critical infrastructure systems in a post-disaster context, by:</td>
<td>The resilience of the network can be improved by investments in infrastructure</td>
<td>Government, stakeholders, researchers, students</td>
</tr>
<tr>
<td>- Mitigating CIS failure, disruption, and damage;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Promoting better physical conditions for systems to work;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Ensuring continuity of flow of people and goods.</td>
<td></td>
<td>Define the Objectives</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Develop the Hypothesis</th>
<th>Test the Hypothesis</th>
<th>Draw Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>The hypothesis is built by constructing the model including the components of the “System Dynamic Diagram of Decision Support System for Critical Infrastructure System Resilience”. The model developed used a mix of different possible infrastructures including Main Chain and Attribute Tracking.</td>
<td>The model is large, complex; allow to identify problems and to fix them without having to rebuild the whole model. It also allows minor changes for using converters instead of flows and stocks as needed. It enables to link different entities that do not share the same units, reflecting real-world dynamics. The model showed and validated the framework represented by the diagram for the Critical Infrastructure Decision Support System. The model can be customized to work with more details and produce aggregated results, transitioning well between the project/operational level and the management/strategic level. The model can continue to grow and include more variables and more interdependency among variables.</td>
<td>Active learning strategy – includes constructing the model and simulating different options for making decisions to improve the resilience of CIS. It allows understanding the need for some specific variables to produce determined results and to modify calculations to adjust to changes through time to reflect infrastructure behavior. It allows verifying feasibility of each step of the model as it is being built. It also requires a continuous learning process not only to enable a good structure to the model, but also to deal with the software tools and interface. It allows working with basic mathematical functions to more elaborate equations. It allows getting insight of things that can be better built. It also allows seeing where the software system platform is limited showing the system behavior in the interface, where graph and tools limits the way the model can be presented and understood to the audience.</td>
</tr>
</tbody>
</table>

| Assess Robustness of Conclusions | | |
|----------------------------------|--------------------------|
| A sensitivity analysis is included in the model. It shows the output of the model working with the current values associated for simulation, and also tests the model assigning random numbers. It proves the model works better for greater frequencies of storms for the case of Delaware and the current parameters included in the model. This shows the model is fairly capturing the real-world problem being investigated. | Through the use of model for simulations, and presentation of the process and results. Includes the key elements for including in the communication part of a Decision Support System. Through the interface enable the audience to capture the main idea of the model, including the possibility for seeing how/what is the model behind the simulation presented. Allows and motivate people to “ask more questions and investigate other possibilities”. |

Source: Croope, Silvana V. based on isee systems (2004).
The overall model for the CIR-DSS begins with the Main Chain infrastructure template in STELLA. The model is adjusted based on the hypothesis test in the next step. If necessary the process is iterated. The related parts of the model that integrate the subsystems of CIR-DSS are also developed, and need to be tested and adjusted to fit the final complete model.

After defining the issue in STELLA, is important to review the 8 steps of the application of the framework. Remember the first step includes choosing a critical infrastructure system, a study area, and hazard. The critical infrastructure system chosen is transportation roads; the study area is Seaford south of Delaware (U.S.A.) focusing the analysis on a limited geographic area; and the hazard is flooding at the scale of a federal disaster (in particular the one happened in June 2006). A preliminary graph to illustrate a reference behavior pattern (RBP) with relative measures (normalizing values) of such infrastructure is shown in Figure 12 and Figure 13 for two circumstances: “as is”, and “to be” respectively.

![Figure 12 Reference Behavior Pattern for System "As Is"
Source: Croope, Silvana, based on USDOT and FHWA (2002).](image)

**Figure 12 Reference Behavior Pattern for System "As Is"**
Source: Croope, Silvana, based on USDOT and FHWA (2002).

*As is* RBP considers a normal process of the transportation network system performance over time, with floods as the type of disaster, and the transportation system back in operation and repaired or reconstructed to the original design. The time spam relates to the occurrence (impact) of a disaster, which relates to the time where the infrastructure is no long in service due to disruption or failure. This time during which the infrastructure is unavailable can vary according to the level of damage or destruction and the required repair or rebuilding. The degradation of the physical condition in the transportation network, in this case, is a secondary factor, not investigated in depth in the model as a factor contributing to speed the need for maintenance and shortening
the infrastructure life-cycle. Also, the assumption is that without infrastructure improvements and mitigation measures adopted (in relation to the improvement of the resilience of the system) a similar behavior pattern is exhibited when another disaster occurs. As a rough approximation, the performance of RBD for the system, shown in Figure 12, degrades, collapses with the occurrence of a major disaster, and is then fixed and the cycle re-starts at the level planned according to the original design. The curve goes down after some oscillations, falls all the way to no functionality and after some time, it goes all the way up and gives place to another phase of going down after some oscillations.

To be RBP considers an improvement of system resilience after disaster(s), an overall recovery and mitigation action combined. This meaning the system could be improved by (any or all of these items):

- reinforcing structures (rebuilding),
- changing the network (e.g. location of roads, bridges),
- adding segments to the network (new construction projects),
- replacing structures with other more resistant features,
- reinforcing building codes for new constructions, and
- any other possibility that adds up effort to reaching a mitigation strategy.

One can expect to see the system better withhold bigger loads of stress, decreasing vulnerability, suffering less with the impact of disaster. Hypothetically, the improvement of the system will reach the level of no absolute/complete disruption or no failure, consequently meaning no big damage or destruction will impact the infrastructure. Of course, in real life, man cannot expect to have things in a “built for ever” condition and a consequent permanent service through time, because disasters can vary per type, intensity, and periods for occurring. Degradation of the transportation network service assumes a more relevant role in this type of scenario, where available roads to enable continuous flow look for existing connected segments. The learning capabilities, technology evolution, and stakeholders will and commitment can also impact the overall outcome of the resilience of an infrastructure system.

The To Be RBP considers the most recent FEMA federal disaster declarations (in terms of years) for flooding, for Sussex County in Delaware where Seaford is located (FEMA 2007a). It helps address the variation among the time of events, a better approach to reality. The improvement of the resilience of a system, for this approach, is independent of the past actions – if such improvements took place or not in the real world, also ignoring that in the real world the evolution and adoption of such actions take a very long time to be adopted and implemented.
The RBD, shown in Figure 13, functions a little differently. The span of time between the occurrence of a major disaster and the system getting back to its function decreases over time. However, the performance of the system, even though improved, does not go above 100%. This is because the repair, rebuilding or even replacing (segments) of the infrastructure, address anticipated events to a certain scale of intensity. The comparison of the system before and after the disaster serves as a basis for improvements that the system needs to decrease its vulnerability, and consequently lessen damage and destruction, which leads to failure. A literal comparison of the system performance pre and post event in terms of percentages, and the structural quality of the infrastructure requires a different graph, and this is not the purpose or priority of this model. However to lessen the impacts of disasters is the purpose for making a system more resilient, which can be seen as making the infrastructure system performance more stable and continuous through time.

As part of developing a hypothesis, the definition of an infrastructure-base (a dynamic organizing principle), the Attribute Tracking infrastructure base is at the core of the CIRDSS model. The feedback shown in the Framework Dynamic Diagram is incorporated in the model by connecting key variables to the calculations for the results being searched for. The model in STELLA does not allow for a “simplistic” representation of a feedback loop by positioning connectors in opposition to the direction of the model calculations. This would build a round/circular flow/movement, for which there would be no end and no evolving perspective. The system has to leave an open end to enable the change of the RBP, and capture changes through time.

To define the model framework, start by specifying what is flowing in this system, the key actors, and/or the most important accumulation/activity. If the most important...
activity is an accumulation, a stock is the representative of the heart of the issue, in this case, the transportation infrastructure in terms of roads (segments) and bridges. With this definition, now it is possible to add inflow and outflow. If the most important activity is not an accumulation, then the main diagram present in the model will not be a stock with flows, but converters. However, it is important to make sure quantities are represented and use as best as possible the stock and flow diagrams and benefit from their type of operations.

A good start for building the model in STELLA, again, is by reviewing the eight steps for the application of the CIR-DSS framework. The types of diagram considering the functions they can carry are assigned to each variable based on the CIR-DSS framework either being a stock, a flow, a decision process diamond, or a converter. The connections established among them by using connectors are the key elements to making the model a tool that enables simulation involving variables from different subsystems. As the model is built, the framework is actually being tested – it is testing the hypothesis for addressing the complex problem involving infrastructure system decision-making process focusing in disasters. During this process one learns how the STELLA software works, but mainly learns what and how the system being analyzed needs and depends on each other variables to work.

One important element in using this system is that only one flow template per flow must be used at a time to characterize flows as it works in reality. The last version of the model has a predominant use of converters (e.g., resilience, projects, results evaluation and communication). The “Decision Process Diamond” was not used because it is in fact a “placeholder” for including sub-model calculations.

**Summary and Related Work**

This working paper provides an overview of the process of developing models in STELLA. Other working papers address:

- Working with HAZUS-MH (Croope 2009)
- Building the Model in STELLAR
- Building the Interface in Stellar

**Acknowledgements**

The author would like to thank the University of Delaware, University Transportation Center, and the Delaware Department of Transportation for sponsoring this research.

The author would also like to thank PhD Sue McNeil, professor in the Department of Civil and Environmental Engineering, President of the Disaster Research Center, and Adviser for all the hard work, guidance, motivation, and strength to carry this research all the way to its findings.
References


